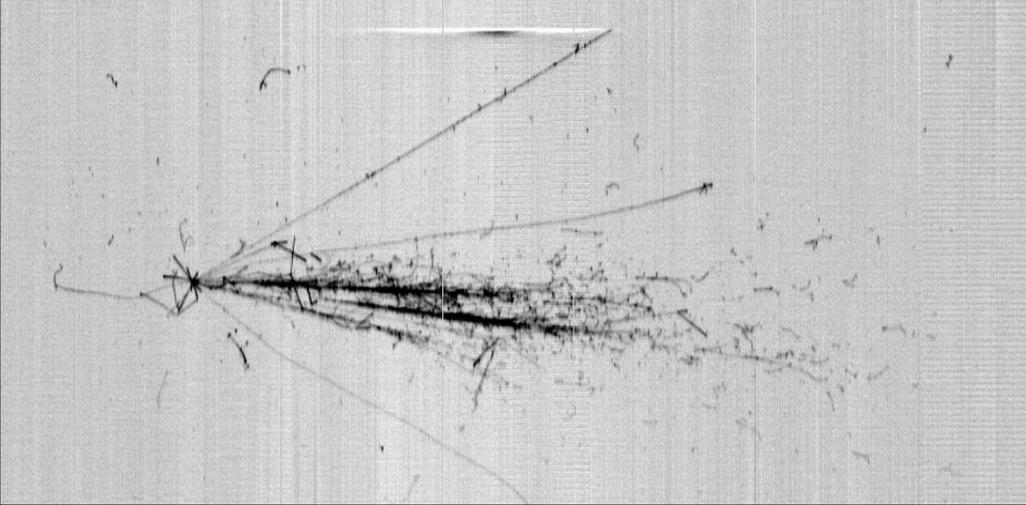


ICARUS T600: status and perspectives for sterile neutrino searches at FNAL

Alessandro Menegolli
University and INFN Pavia

*on behalf of the ICARUS
Collaboration*



*International Workshop for the Next Generation Neutron
Decay and Neutrino Detector (NNN2015) - 28/10/2015*

The ICARUS Collaboration

M. Antonello⁸, P. Aprili⁸, B. Baibussinov⁴, F. Boffelli³, A. Bubak¹⁴, E. Calligarich³, N. Canci⁸, S. Centro⁴, A. Cesana¹⁰, K. Cieslik⁶, A.G. Cocco¹¹, A. Dabrowska⁶, A. Dermenev¹², A. Falcone³, C. Farnese⁴, A. Fava⁴, A. Ferrari¹, D. Gibin⁴, S. Gninenko¹², A. Guglielmi⁴, M. Haranczyk⁶, J. Holeczek¹⁴, A. Ivashkin¹², M. Kirsanov¹², J. Kisiel¹⁴, J. Lagoda¹⁸, S. Mania¹⁴, A. Menegolli³, G. Meng⁴, C. Montanari³, S. Otwinowski¹⁷, P. Picchi⁷, F. Pietropaolo⁴, P. Płoński¹³, A. Rappoldi³, G. L. Raselli³, M. Rossella³, C. Rubbia^{*1,5,8}, P. Sala¹⁰, A. Scaramelli¹⁰, E. Segreto⁸, F. Sergiampietri¹⁹, D. Stefan¹⁰, R. Sulej¹⁶, M. Szarska⁶, M. Terrani¹⁰, M. Torti³, F. Varanini⁴, S. Ventura⁴, C. Vignoli⁸, H.G. Wang¹⁷, X. Yang¹⁷, A. Zalewska⁶, A. Zani³, K. Zaremba¹³

+ new WA104 members:

V. Bellini², P. Benetti³, S. Bertolucci¹, H. Bilokon⁷, M. Bonesini⁹, J. Bremer¹, N. Golubev¹², U. Kose¹, F. Mammoliti², G. Mannocchi⁷, D. Mladenov¹, M. Nessi¹, M. Nicoletto⁴, F. Noto¹, R. Potenza², J. Sobczyk¹⁵, M. Spanu³, C.M. Sutura², F. Tortorici², T. Wachala⁶

¹CERN, Geneva, Switzerland

²Department of Physics, Catania University and INFN, Catania, Italy

³Department of Physics, Pavia University and INFN, Pavia, Italy

⁴Department of Physics and Astronomy, Padova University and INFN, Padova, Italy

⁵GSSI, Gran Sasso Science Institute, L'Aquila, Italy

⁶Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Science, Kraków, Poland

⁷INFN LNF, Frascati (Roma), Italy

⁸INFN LNGS, Assergi (AQ), Italy

⁹INFN Milano Bicocca, Milano, Italy

¹⁰Politecnico and INFN Milano, Milano, Italy

¹¹INFN Napoli, Napoli, Italy

¹²Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

¹³Institute for Radioelectronics, Warsaw University of Technology, Warsaw, Poland

¹⁴Institute of Physics, University of Silesia, Katowice, Poland

¹⁵Institute of Theoretical Physics, Wrocław University, Wrocław, Poland

¹⁶National Centre for Nuclear Research, Warsaw, Poland

¹⁷Department of Physics, UCLA, Los Angeles, California, USA

¹⁸National Centre for Nuclear Research, Otwock, Swierk, Poland

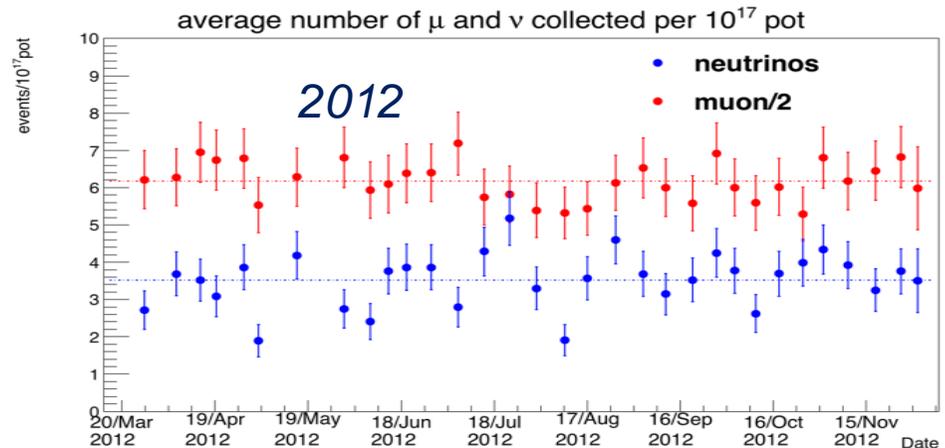
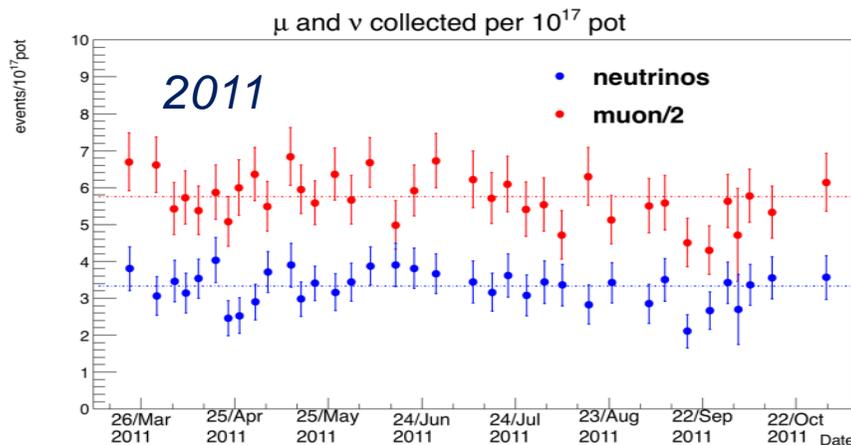
¹⁹University of Pisa and INFN, Pisa, Italy

*+ ICAR-US : 6 new US groups:
Colorado Univ., Pittsburgh Univ.,
SLAC, FNAL, Argonne, Los Alamos*

**Spokesperson*

Evolution of LAr-TPC detectors

- Cherenkov detectors in water/ice and liquid scintillator detectors have been main technologies so far for neutrino and rare event physics. *Unfortunately these detectors do not permit to identify unambiguously each ionizing track.*
- *As an alternative, the LAr-TPC technique, effectively an electronic bubble-chamber, was originally proposed by C. Rubbia in 1977 [CERN-EP/77-08], supported by Italian Institute for Nuclear Research (INFN).*
- *Thanks to ICARUS collaboration, LAr-TPC has been taken to full maturity with the T600 detector (0.6 kton) receiving CNGS neutrino beam and cosmic rays.*
- *ICARUS concluded in 2013 a very successful 3 years long run at LNGS, collecting 8.6×10^{19} pot event with a detector live time $> 93\%$, recording 2650 CNGS neutrinos (in agreement with expectations) and cosmic rays (0.73 kty).*



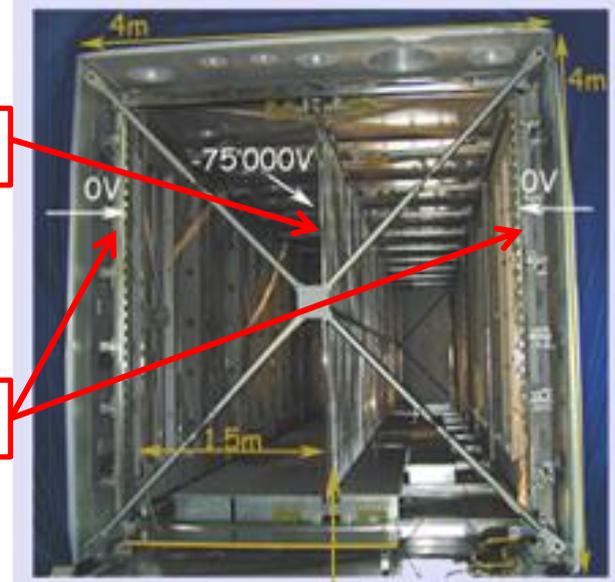
The ICARUS detector @ LNGS



LNGS -Hall B

LN₂ storage

T600



cathode

TPC wires

Two identical modules...

- $3.6 \times 3.9 \times 19.6 \text{ m} \approx 275 \text{ m}^3$
- Total active mass $\approx 476 \text{ ton}$

... and four wire chambers

- Two TPCs for each module, divided by the cathode $\rightarrow 1.5 \text{ m}$ drift length
- $HV = -75 \text{ kV} \rightarrow E_{\text{drift}} = 0.5 \text{ kV/cm}$
- $v_{\text{drift}} = 1.55 \text{ mm}/\mu\text{s}$

Detectors

- 3 wire planes per TPC ($0^\circ, \pm 60^\circ$)
- ≈ 54000 total wires ($150 \mu\text{m} \text{ } \varnothing$, 3 mm pitch)
- $54+20$ photomultipliers ($8'' \text{ } \varnothing$) + wls (TPB), sensitive at 128 nm (VUV)

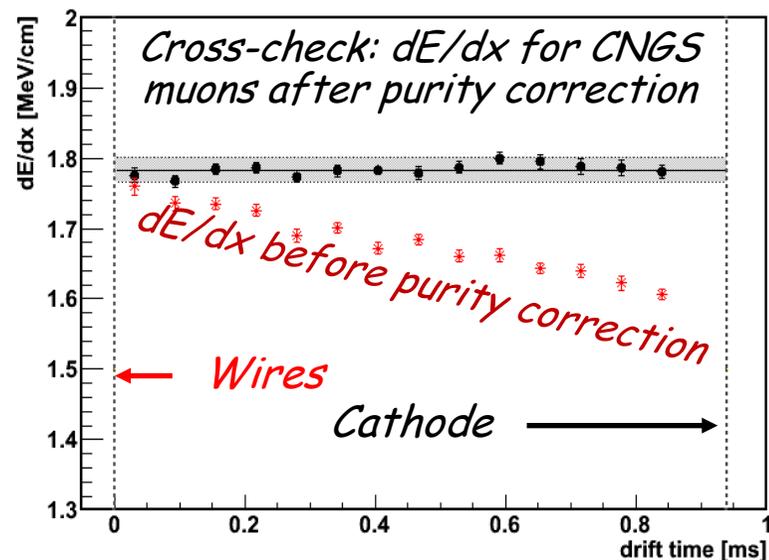
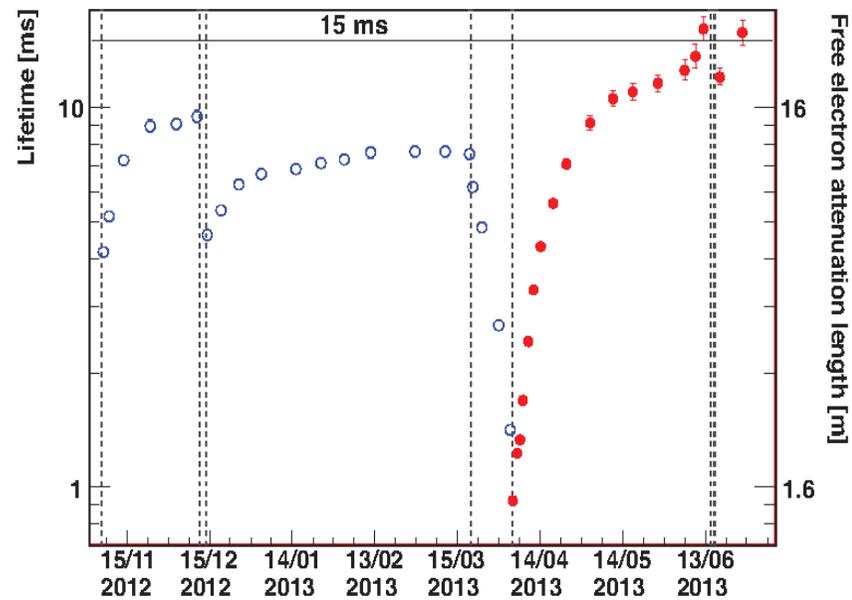
Electronics

- FADC 10bit $1\text{mV}/\text{ADC} \sim 1000e^-/\text{ADC}$

The key features of LAr imaging: very long e-mobility

- Level of electronegative impurities in LAr must be kept exceptionally low to ensure \sim m long drift path of ionization e^- with very small attenuation.
- New industrial purification methods developed to continuously filter and re-circulate both in liquid ($100 \text{ m}^3/\text{day}$) and gas ($2.5 \text{ m}^3/\text{hour}$) phases.
- Electron lifetime measured during ICARUS run at LNGS with cosmic μ 's: $\tau_{ele} > 7 \text{ ms}$ ($\sim 40 \text{ p.p.t. } [\text{O}_2] \text{ eq}$) $\rightarrow 12\% \text{ max. charge attenuation}$.
- With the new pump installed at the end of LNGS run: $\tau_{ele} > 15 \text{ ms}$ ($\sim 20 \text{ p.p.t.}$).

ICARUS demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors $\sim 5 \text{ m}$ drift as required for DUNE project.



ICARUS LAr-TPC performance

- **Tracking device:** precise $\sim\text{mm}^3$ resolution, 3D event topology, accurate ionization measurement;
- **Global calorimeter:** total energy reconstruction by charge integration - excellent accuracy for contained events; momentum of non contained μ determined via Multiple Coulomb Scattering $\Delta p/p \sim 15\%$ in 0.4-4 GeV/c range;
- **Measurement of local energy deposition dE/dx :** e/γ remarkable separation (0.02 X_0 sampling, $X_0=14$ cm particle identification by dE/dx vs range);

➤ **Low energy electrons:**

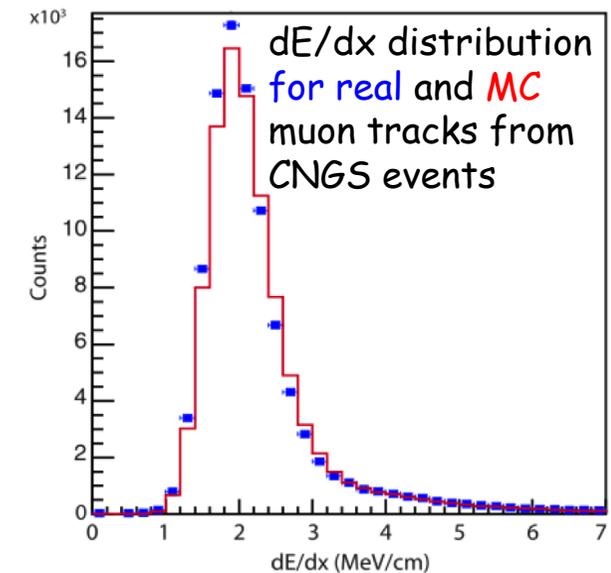
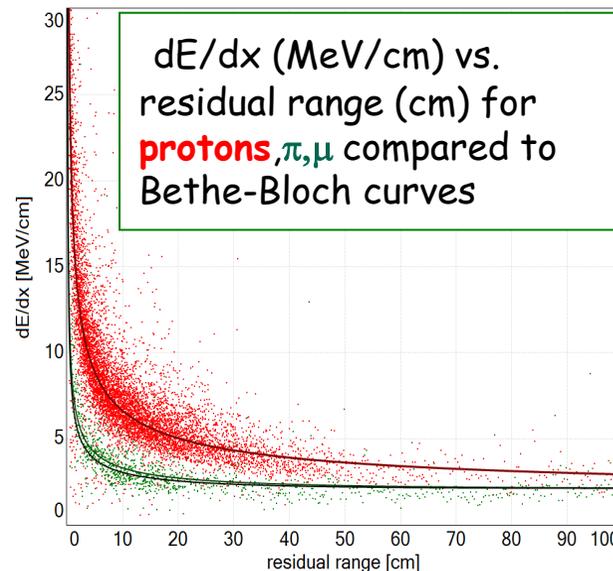
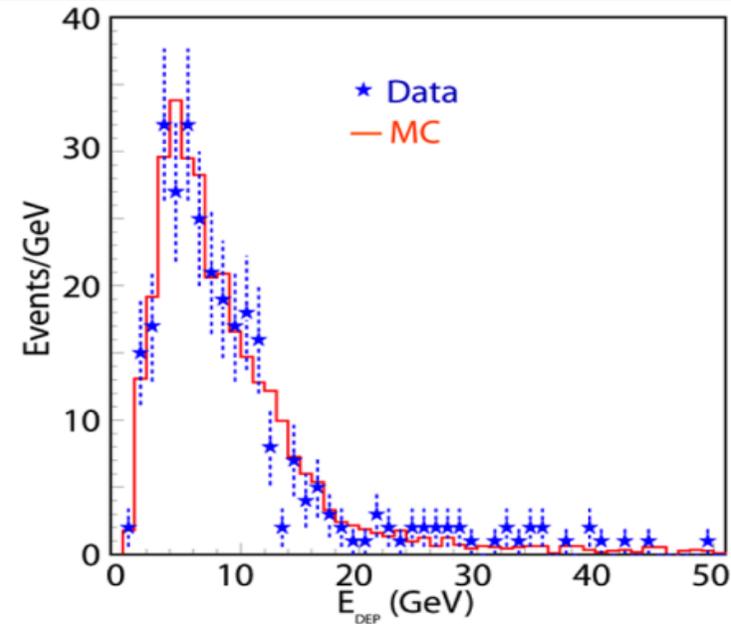
$$\sigma(E)/E = 11\%/\sqrt{E(\text{MeV})} + 2\%$$

➤ **Electromagnetic showers:**

$$\sigma(E)/E = 3\%/\sqrt{E(\text{GeV})}$$

➤ **Hadron shower (pure LAr):**

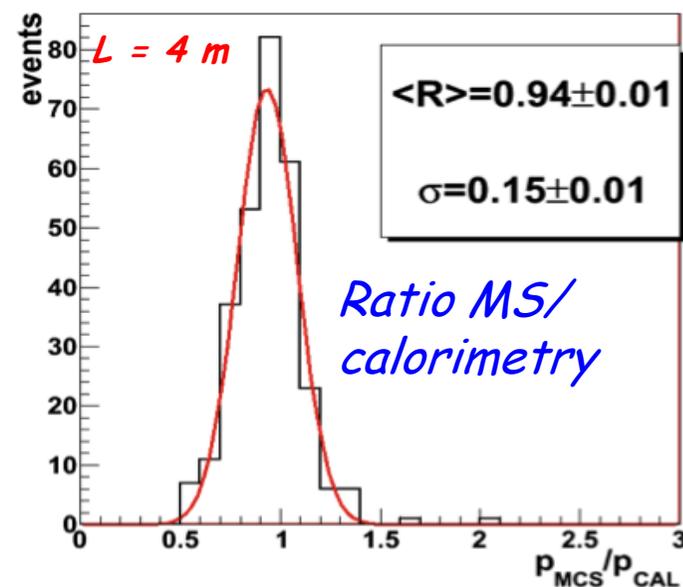
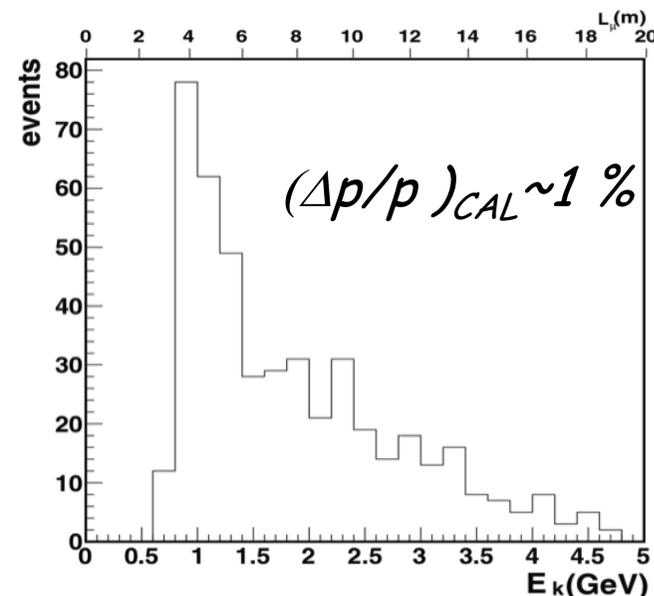
$$\sigma(E)/E \approx 30\%/\sqrt{E(\text{GeV})}$$



Measurement of muon momentum via multiple scattering

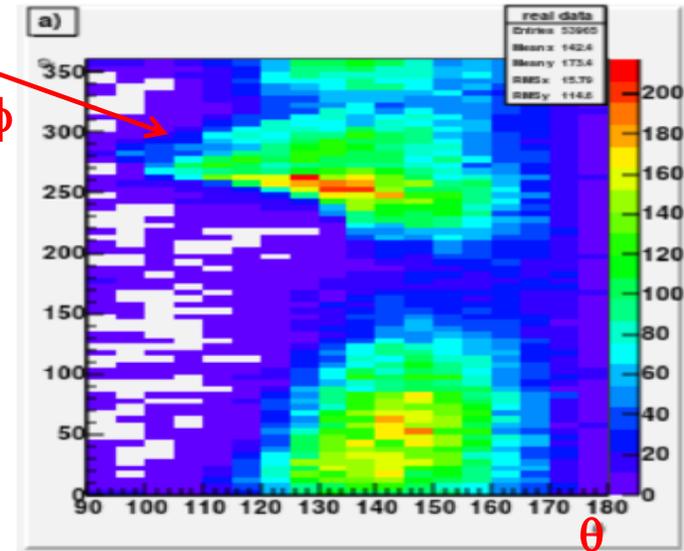
- Multiple Coulomb Scattering (MCS) is the only way to measure momentum of non-contained muons.
- Algorithm validated on ~ 400 *stopping muons*: produced in $\nu_{\mu}CC$ interactions of CNGS neutrinos upstream of T600, and stopping/decaying inside the detector.
- Good agreement between MCS and calorimetric measurements.
- Average resolution of $\sim 15\%$ on the stopping muon sample.
- Resolution depends both on momentum and effective muon track length used for measurement.

Some deviations for $p > 3.5$ GeV/c induced by non-perfect planarity of TPC cathode

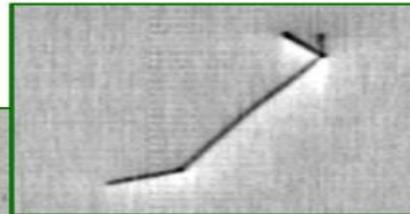


Search for atmospheric ν 's

- Preparatory step: automatic 3D reco of cosmic μ 's
- An algorithm for filtering of interaction vertex and multi-prong event topology has been developed, complemented by visual scanning;
- *Work in progress*: 2 muon-like and 2 NC-like atmosph. ν candidates have been identified in 3 week data recording ($1 \pm 0.4 \mu\text{-CC}$, $1 \pm 0.4 e\text{-CC}$ and 0.4 ± 0.2 NC expected)



Induction 2



Collection

NC atm. candidate: $E_{\text{DEP}} \sim 200 \text{ MeV}$

- 2 charged particles emerge from interaction vertex
- π track: 63 cm (interacting and generating 2 protons)

Collection

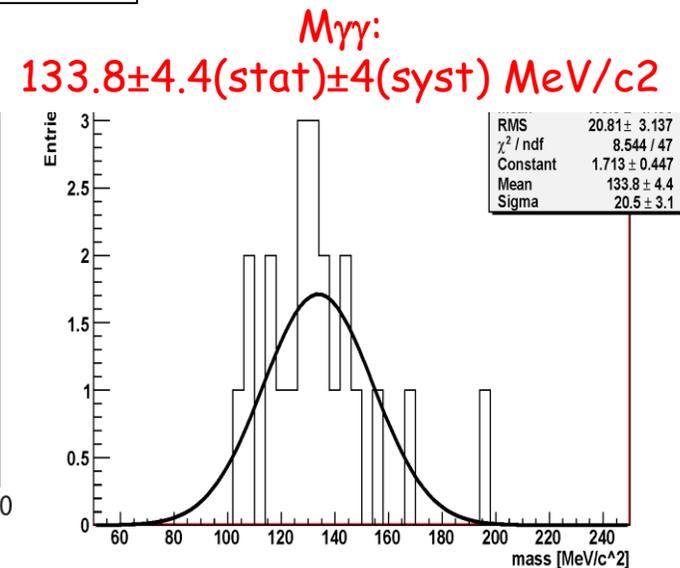
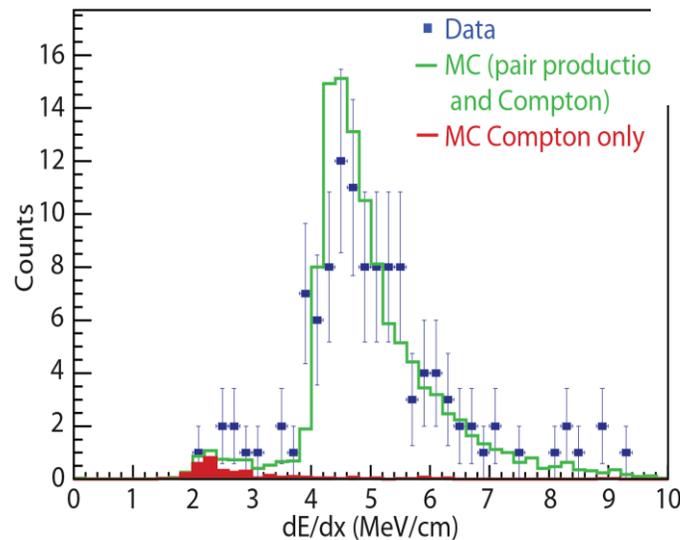
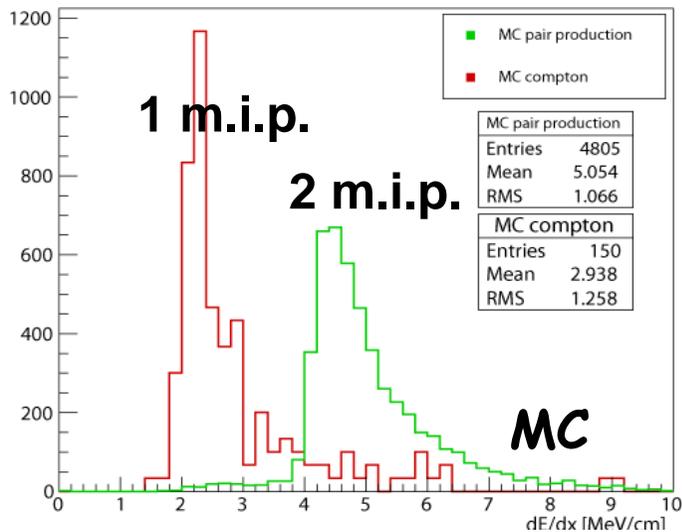
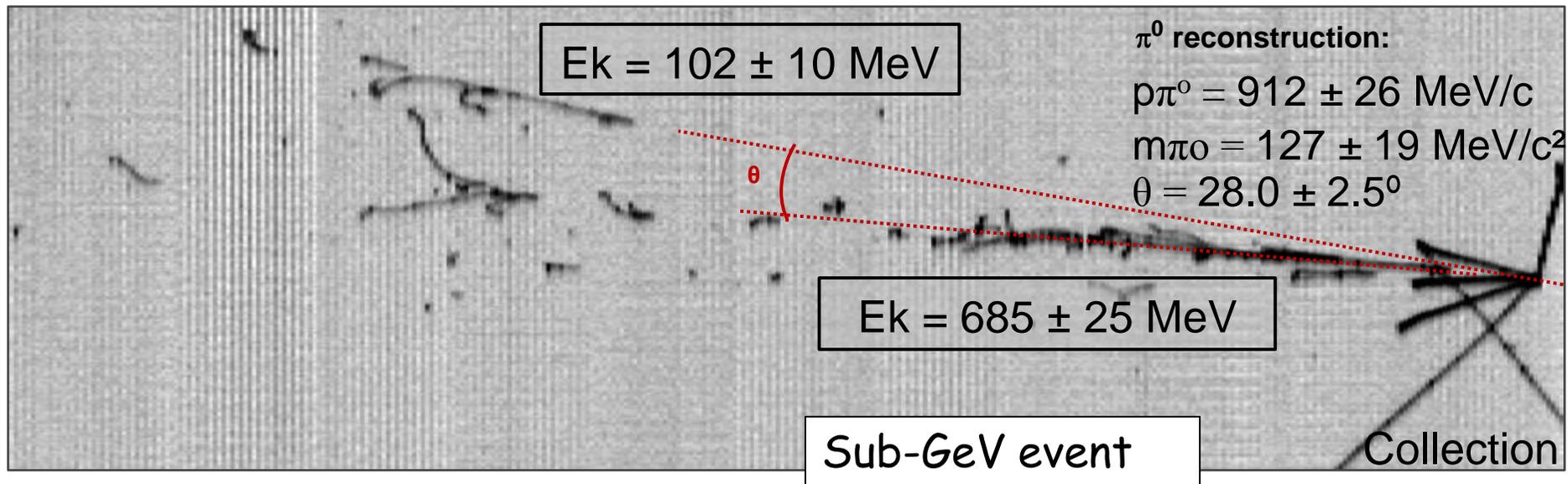
$\nu\mu$ CC atm. candidate: $E_{\text{DEP}} \sim 350 \text{ MeV}$

- μ and p/π tracks are visible
- μ track candidate: 124 cm

Induction 2

~ 200 atm. ν expected for 0.73 kt y exposure

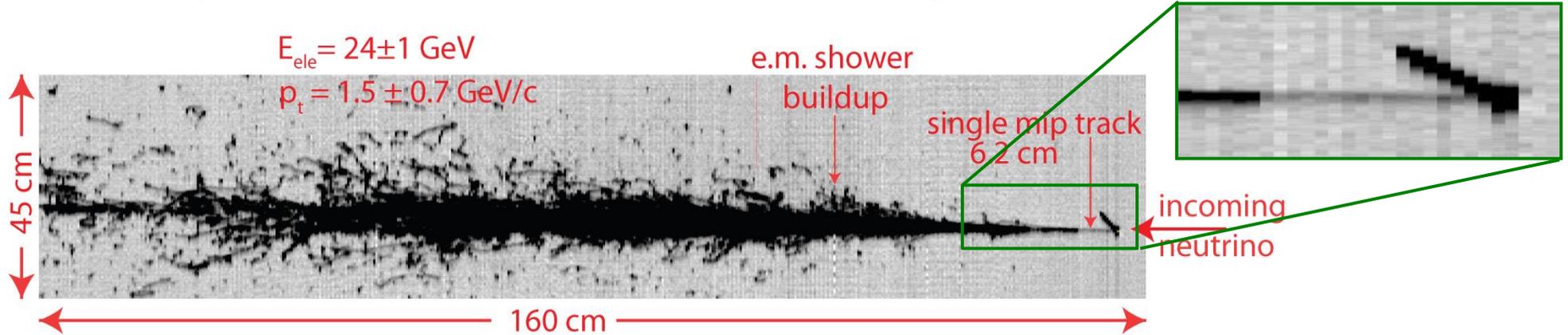
e/γ separation and π^0 reconstruction in ICARUS



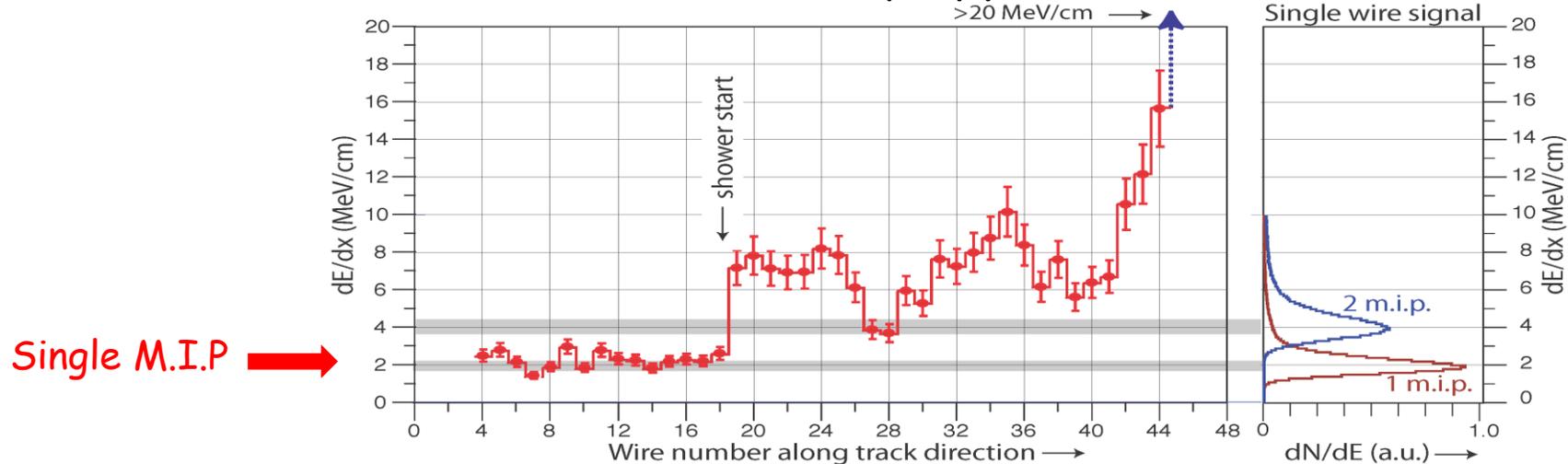
Unique feature of LAr to distinguish e from γ and reconstruct π^0
 → Negligible background from π^0 in NC and ν_μ CC estimated from MC/scanning

ν_e identification in ICARUS LAr-TPC

- The unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.



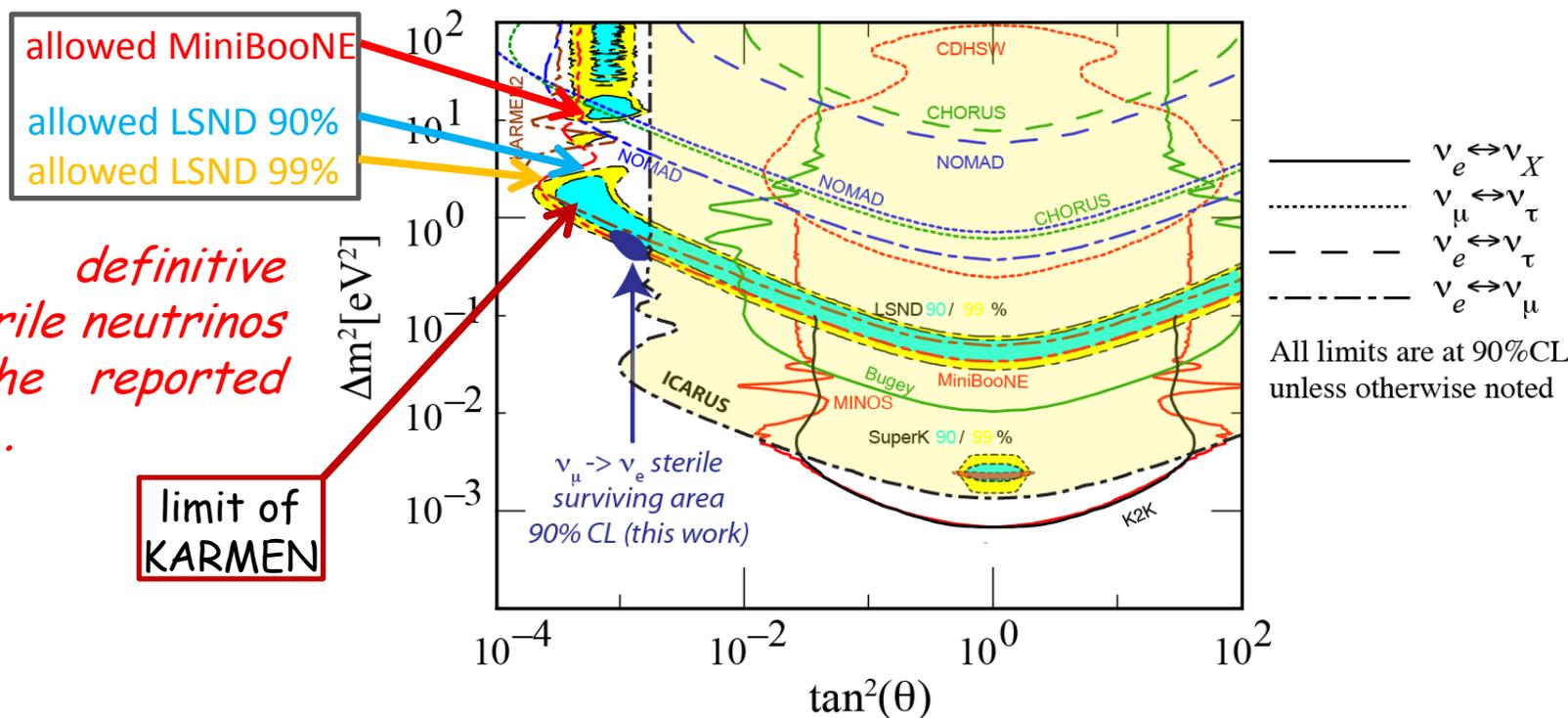
- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.



Search for LSND-like anomaly by ICARUS at LNGS

- ICARUS searched for ν_e excess related to LSND-like anomaly on the CNGS ν beam ($\sim 1\%$ intrinsic ν_e contamination, $L/E\nu \sim 36.5$ m/MeV). No excess was observed: number of ν_e events as expected in absence of LSND signal.
- Analysis on 7.23×10^{19} pot event sample provided the limit on the oscillation probability $P(\nu_\mu \rightarrow \nu_e) \leq 3.85$ (7.60) $\times 10^{-3}$ at 90 (99) % C.L.
- ICARUS result indicates a very narrow region ($\Delta m^2 \sim 0.5$ eV², $\sin^2 2\theta \sim 0.005$) where all experimental results can be accommodated at 90% CL.

Need for a definitive experiment on sterile neutrinos to clarify all the reported neutrino anomalies.



SBN Sterile neutrino search at FNAL Booster ν beamline

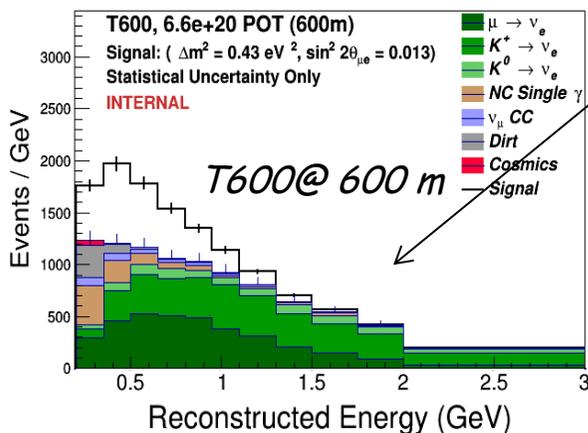
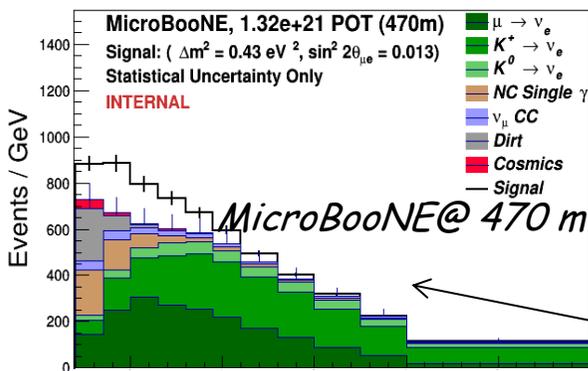
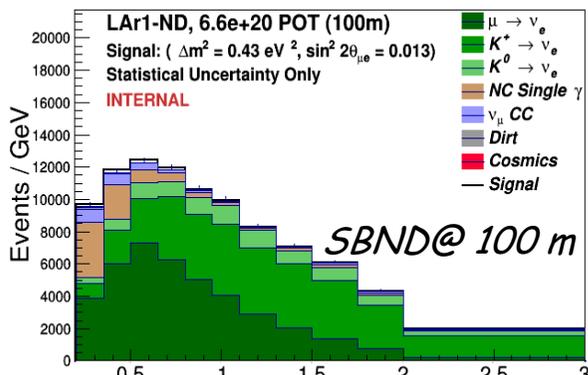
- Joint ICARUS/SBND/MicroBooNE CDR received *Stage 1 Approval* from FNAL PAC Jan 2015. Three LAr-TPC's at different distances from target: **SBND (82 t), MicroBooNE (89 t) and ICARUS (476 t) at 100, 470 and 600 m.**
- The experiment will likely clarify LSND/MiniBooNE, Gallex, reactor anomalies by precisely/independently measuring both ν_e appearance and ν_μ disappearance, mutually related through

$$\sin^2(2\mathcal{G}_{\mu e}) \leq \frac{1}{4} \sin^2(2\mathcal{G}_{\mu x}) \sin^2(2\mathcal{G}_{ex})$$

- In absence of "anomalies", three detector signals should be a close copy of each other for all experimental signatures.
- During its SBN operations, ICARUS will collect also ~ 2 GeV ν_e CC events with NUMI Off-Axis beam, an asset for the long baseline LAr project at FNAL:
 - accurate determination of cross sections in LAr ;
 - experimental study of all individual CC/NC channels to realize algorithms improving the identification of ν interactions.

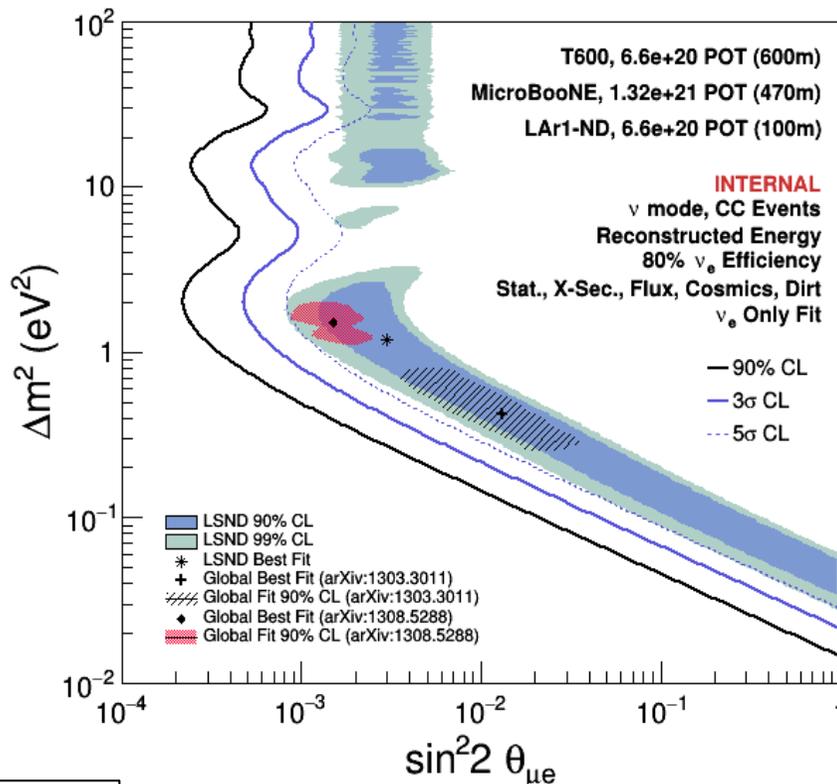
$\nu_\mu \rightarrow \nu_e$ appearance sensitivity

- Expected exposure sensitivity of $\nu_\mu \rightarrow \nu_e$ oscillations for 3 years - $6.6 \cdot 10^{20}$ pot BNB positive focusing (6 years for MicroBooNE).



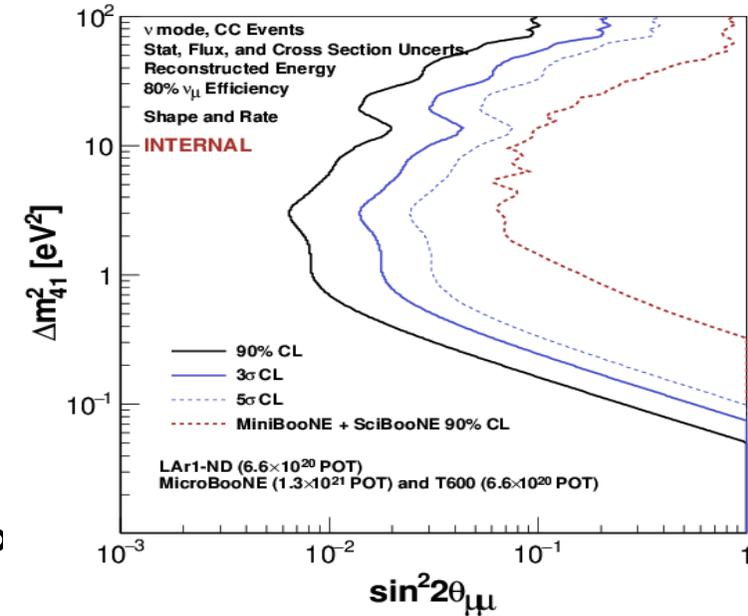
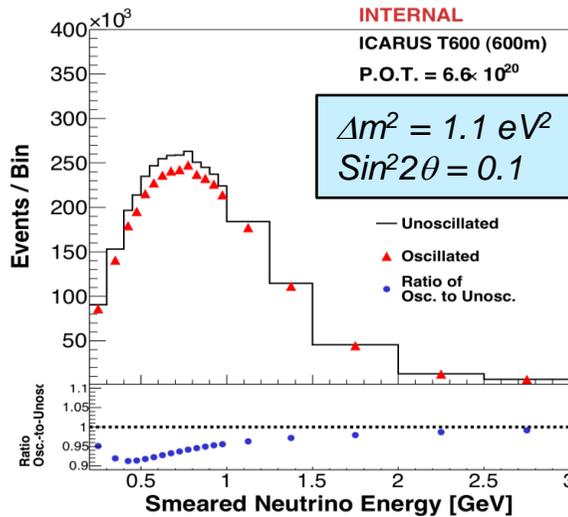
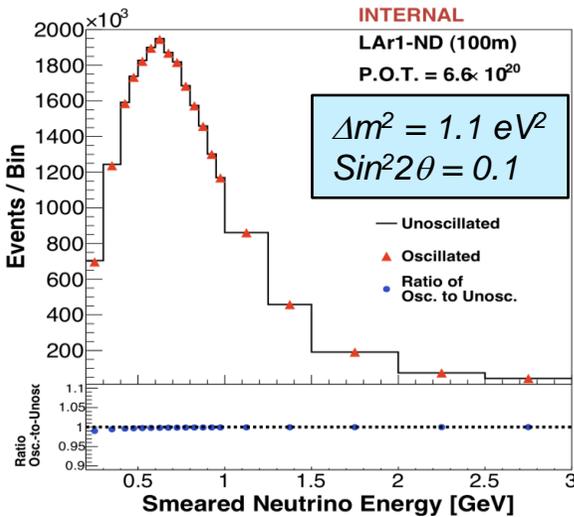
Example for
 $(\sin^2(2\theta)=0.013$
 $\Delta m^2=0.43 \text{ eV}^2)$

*In absence of oscillations,
the spectra should be
copies of each other*



The LSND 99%CL region
is covered at $\sim 5\sigma$ level

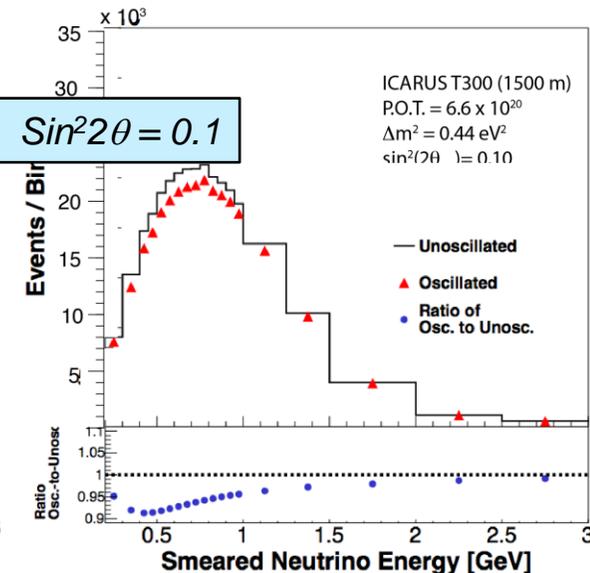
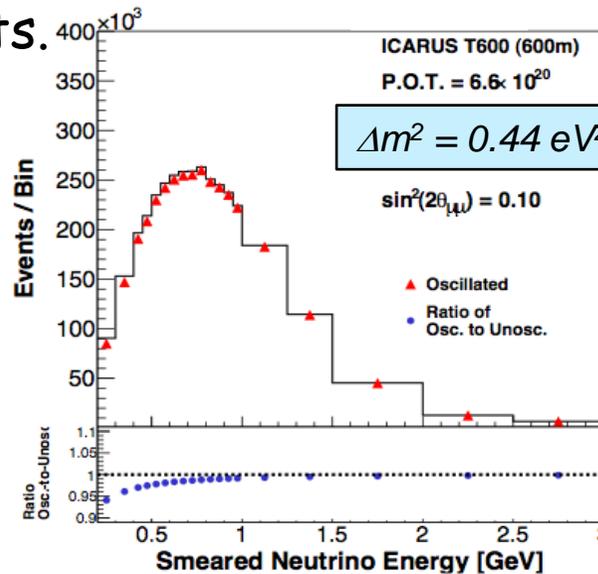
ν_μ disappearance sensitivity



- High event rates/ correlations between 3 LAr-TP will allow extending sensitivity by one order of magnitude beyond present limits.

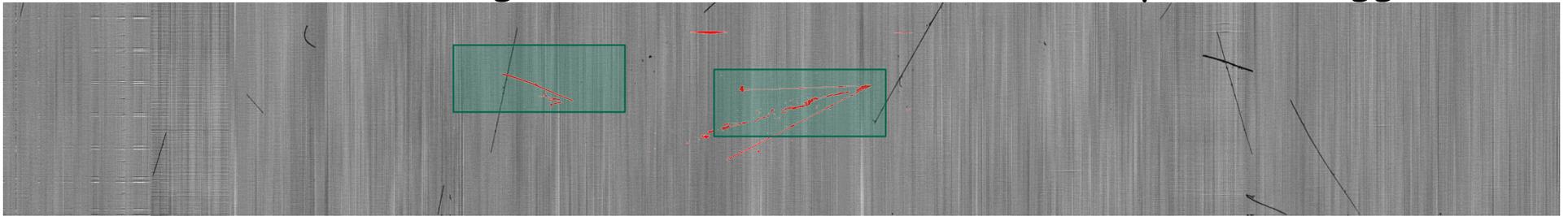
- However for $\Delta m^2 < 0.5 \text{ eV}^2$ ν_μ disappearance at 600 m will be limited at lowest ν energy bins 0.2-0.4 GeV.

- *In order to amplify the effect we may move at a later stage one ICARUS T300 module to 1500 m distance.*



Facing a new situation: the LAr-TPC near the surface

- At shallow depth ~ 12 uncorrelated cosmic rays will occur in T600 during 1 ms drift window readout at each triggering event.
- This represents a new problem compared to underground operation at LNGS: the reconstruction of the true position of each track requires associating to each element of TPC image the occurrence time with respect to trigger time.

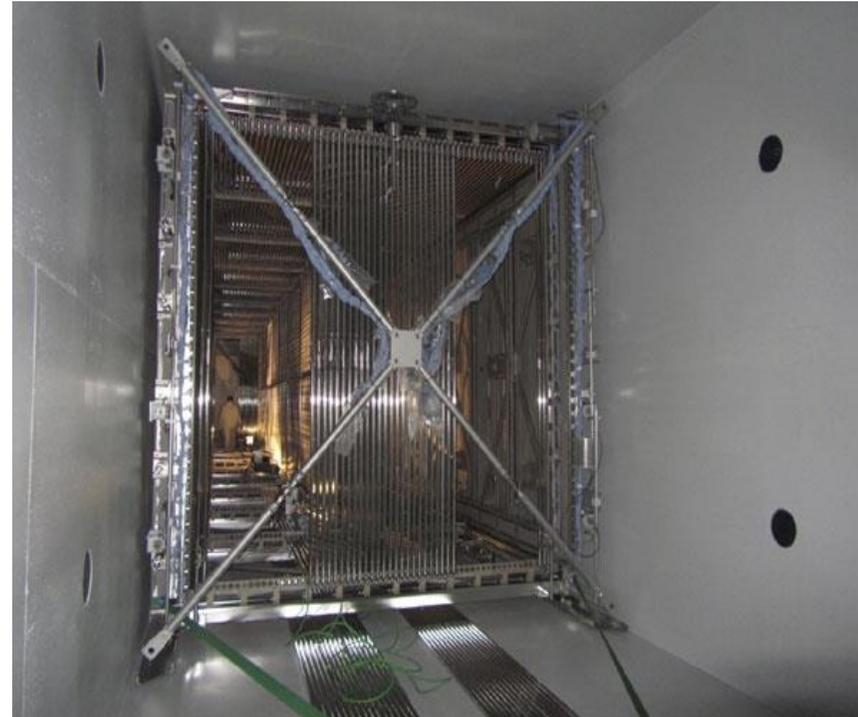


Cosmic rays + low energy CNGS beam events

- Moreover, γ 's associated with cosmic μ 's represent a serious background for the ν_e appearance search since *electrons* generated in LAr via Compton scattering/pair production can mimic a ν_e CC genuine signal.
- A 4π Cosmic Rays Tagger (total surface ~ 1200 m²) of plastic scintillators around the LAr active volume will unambiguously identify all cosmic ray particles entering the detector providing timing/position to be combined with the TPC reconstructed image.

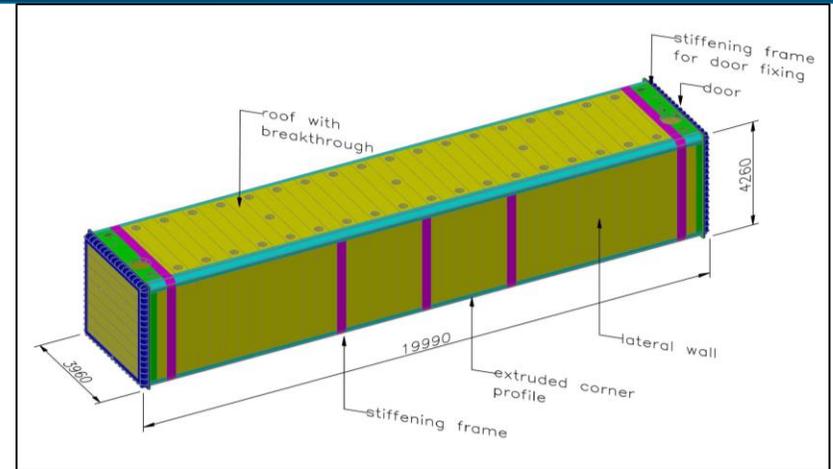
WA104 Project at CERN: overhauling of the T600

- INFN has signed a MoU for **WA104 project at CERN** for T600 overhauling in the framework of CERN Neutrino Platform for LAr-TPC development for short/long baseline neutrino experiment.
 - T600 is being upgraded introducing technology developments **while maintaining the already achieved performance**:
 - new cold vessels (purely passive insulation);
 - refurbishing of cryogenics/purification equipment;
 - a cathode with better planarity;
 - upgrade of the light collection system;
 - new faster, higher-performance read-out electronics.
 - **Common items for ICARUS and other SBN LAr-TPCs**: muon tagging systems to be designed/constructed; tools for event reconstruction have to be developed
- The detector is expected to be transferred to FNAL before end 2016 for installation, commissioning and start of data taking (end 2017).*

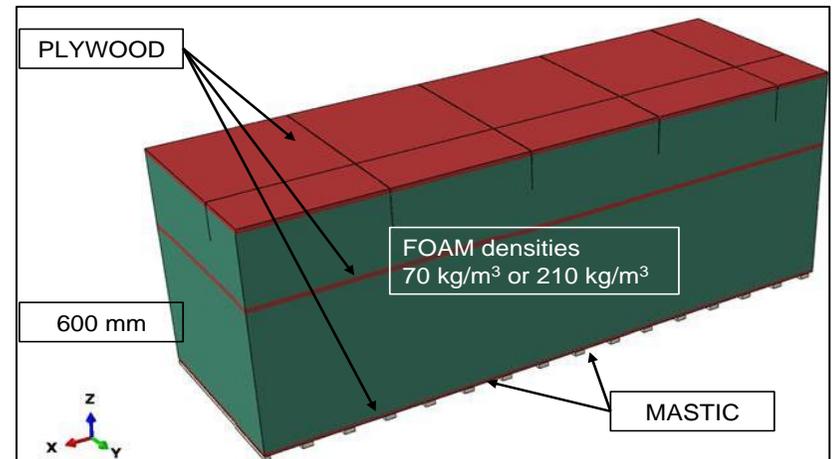


Cold vessels, thermal insulation and cryogenic plant

- New LAr cold vessels made by extruded aluminum profiles welded together: vacuum-tight double-walled container. Completion of the first vessel foreseen by the start of 2016; second one ready ~6 months later.



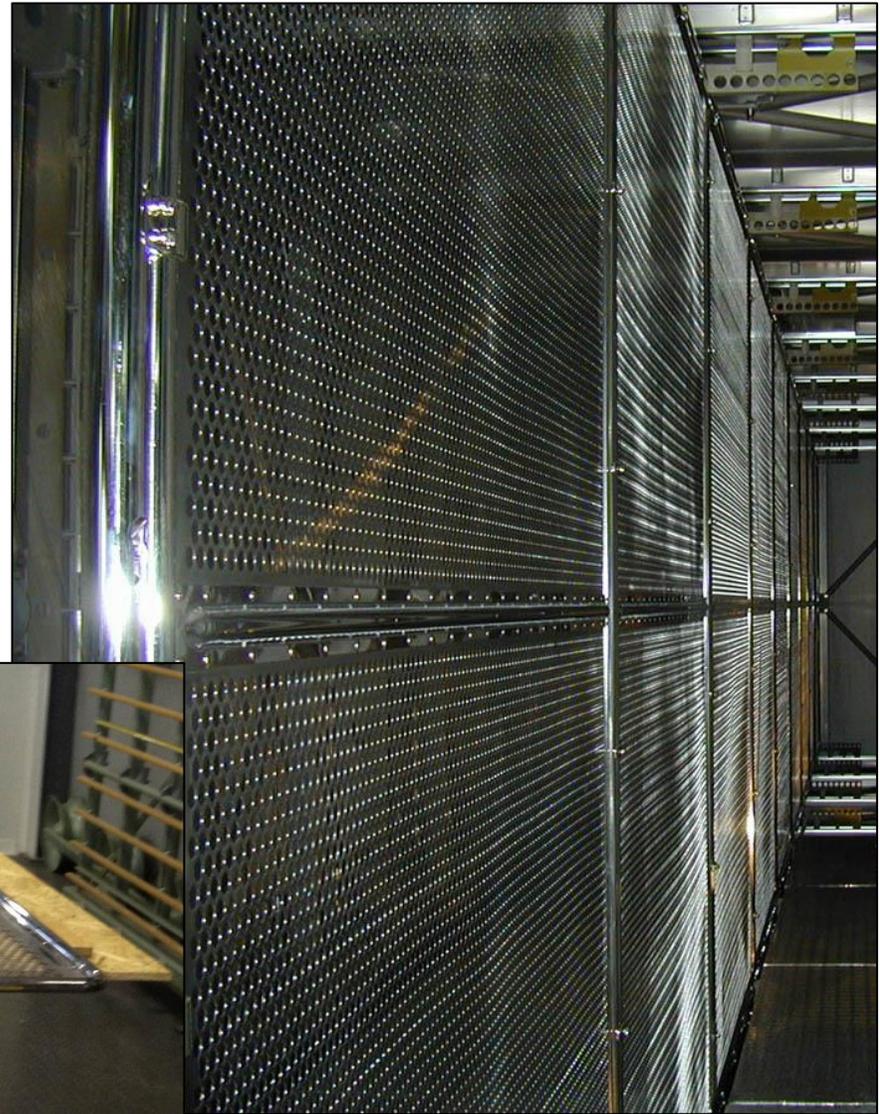
- Purely passive insulation coupled to a renovated, standard cooling shield with two-phase Nitrogen. Expected heat loss through the insulation: ≈ 6.6 kW (10 - 15 W/m²)



- The original layout of the T600 cryogenic/purification plant is being revised: it will be re-organized into self-consistent sub-units (skids) to be built and fully tested at CERN, prior to delivery to FNAL. Re-usable components from the old installation are being selected.

Cathode panel flattening

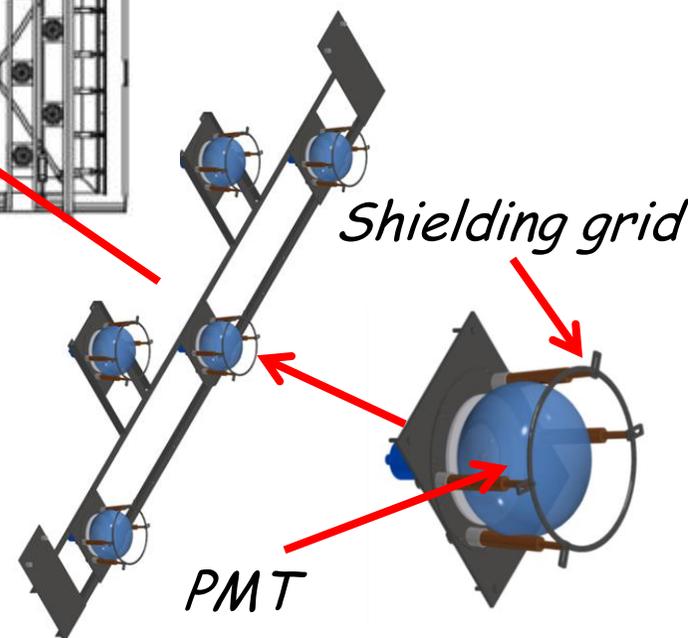
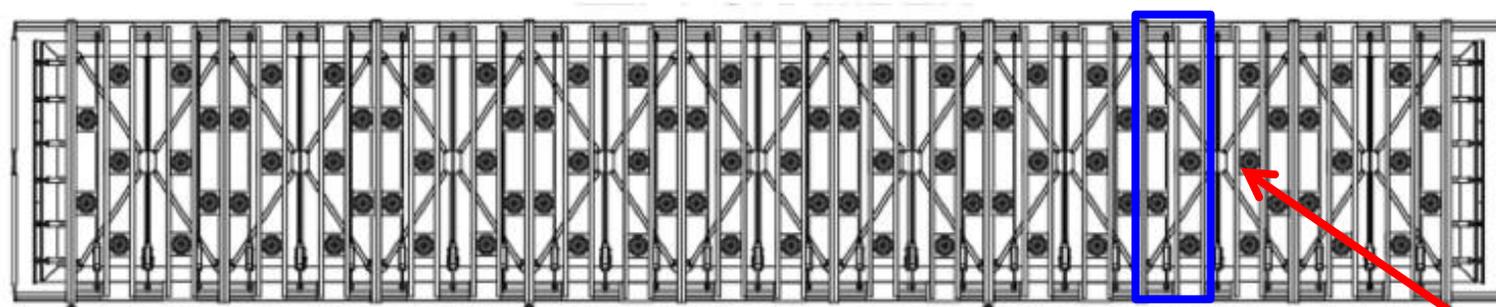
- The old cathode panels were dismantled and thermally flattened with the help of CERN main workshop.
- Original deformations were reduced from around 2.5 cm to few mm.
- The re-installation inside the TPC will be completed within October.



Upgraded Light Collection System

Large surface, Hamamatsu 8" PMTs will be adopted, as in LNGS, but major improvements in space/time event localization capabilities will be required to reject cosmic backgrounds:

- higher quantum efficiency HAMAMATSU R5912-MOD;
- the T600 light detection system will be extended to 90 PMT per TPC, (5% area coverage). ~15 phe/MeV allowing to efficiently trigger low energy events.

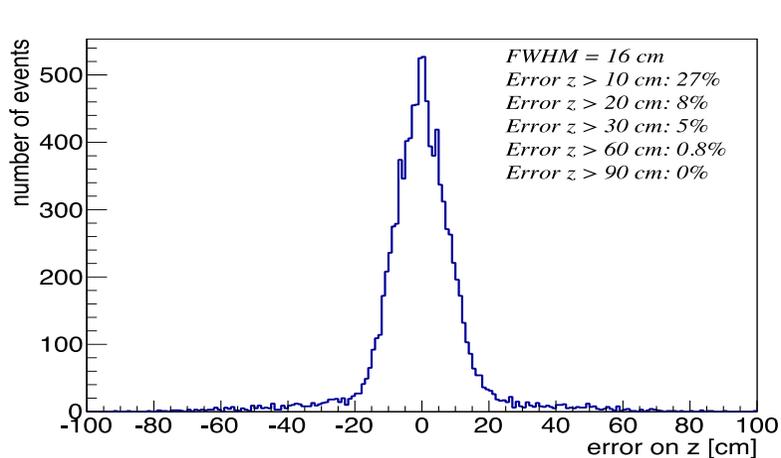


- new voltage divider and shielding, to avoid induced spurious signals on TPC wire planes;
- new mechanical design of the scintillation light collection system;

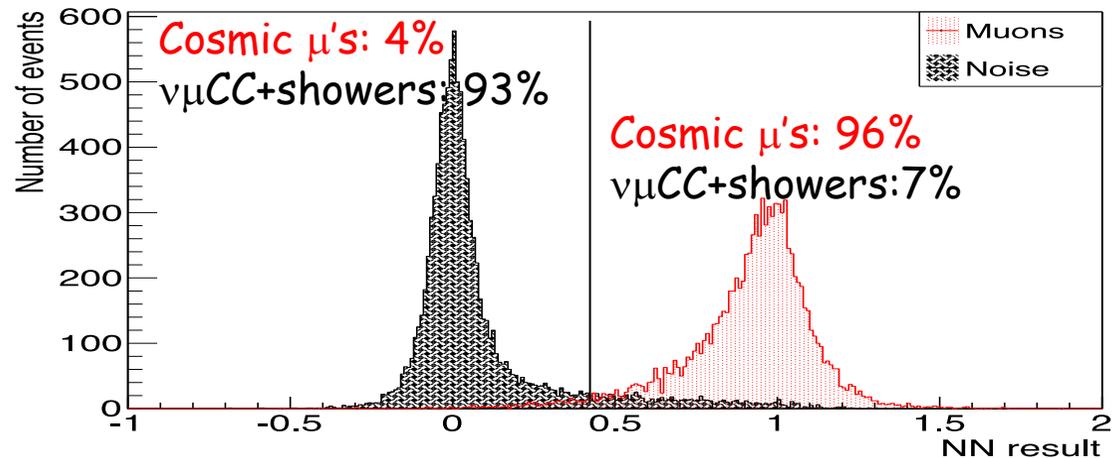
Test, characterization and TPB deposition of all 400 PMTs underway in CERN dedicated labs.

Event localization and identification with PMTs

- Main requirements for the refurbished light detection system:
 - **High detection coverage**, to be sensitive to low E_ν deposition (~ 100 MeV)
 - **High detection granularity**, to localize events and unambiguously associate the collected light to deposited charge;
 - **Fast response - high time resolution**, to be sensitive to timing of each event in the T600 DAQ windows (~ 1 ms); a ~ 1 ns precision is advisable to exploit the 2ns/19ns bunched beam structure .



95 % events localized within 30 cm



Neural Networks can provide a clear cosmic muon identification

Conclusions

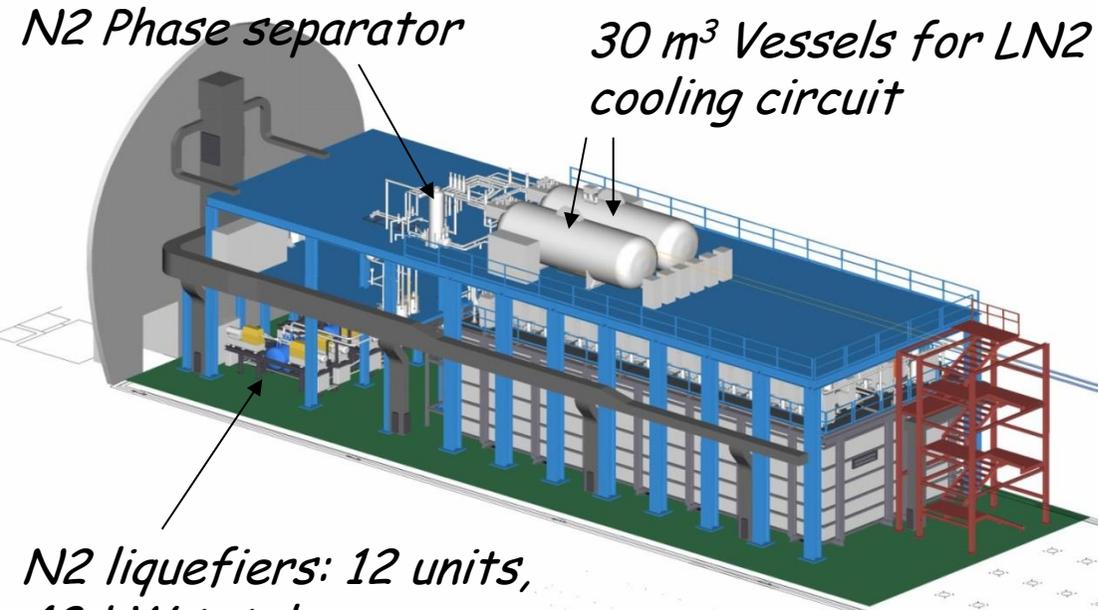
- ICARUS T600 detector has successfully completed the LNGS operation with the CNGS beam, demonstrating that LAr-TPC is *a leading technology for future short/long baseline accelerator driven neutrino physics*.
- The accurate analysis of the CNGS ν events provided **no evidence of oscillation into sterile neutrinos in ICARUS L/E interval**: the global fit of all SBL data + ICARUS limits the window of parameters for a possible LSND anomaly to a very narrow region around 0.5 eV^2 .
- A joint ICARUS/SBND/MicroBooNE collaboration (SBN neutrino experiment at FNAL Booster) has been set up to definitively clarify LSND/MiniBooNE, Gallex, reactor anomalies, profiting of the presence of **three LAr-TPCs at different baselines**.
- The T600 detector has now been **moved to CERN for a significant overhauling** in view of its transportation to FNAL, where it is expected to start data taking by end 2017 with the Booster Neutrino Beam.
- ICARUS will also provide a **significant amount of data** in the energy range of interest for the next Long Baseline experiment.



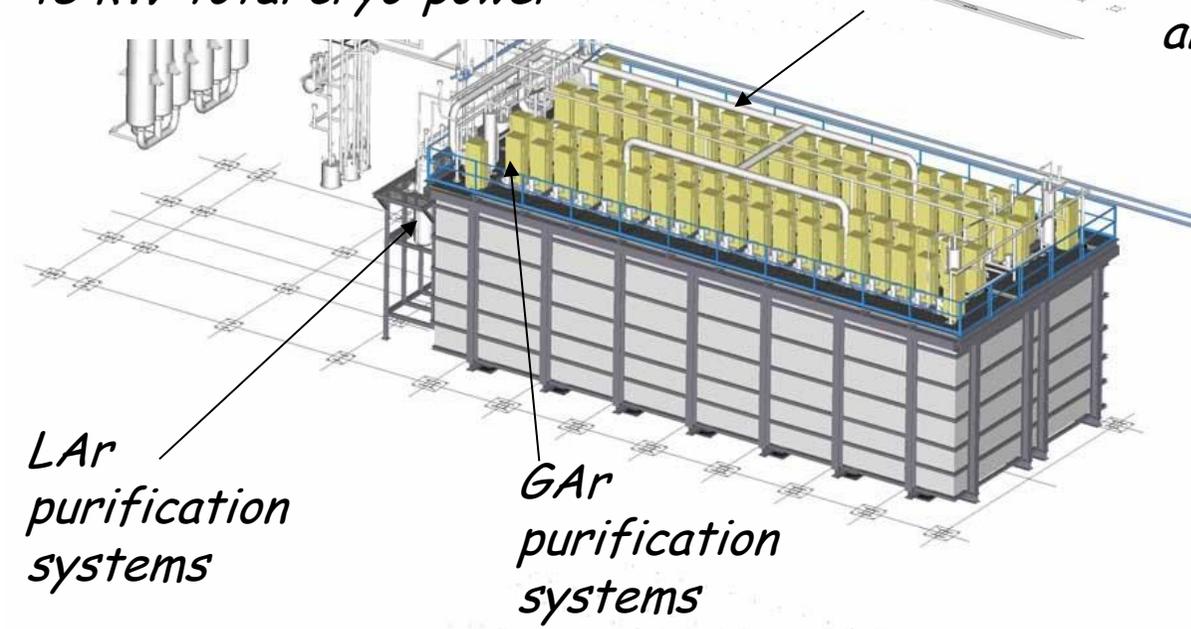
Thank you !

Backup

ICARUS-T600 @ LNGS Hall B: 0.77 kton LAr-TPC

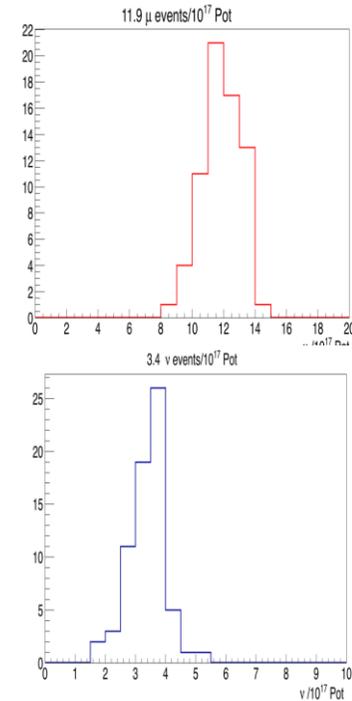
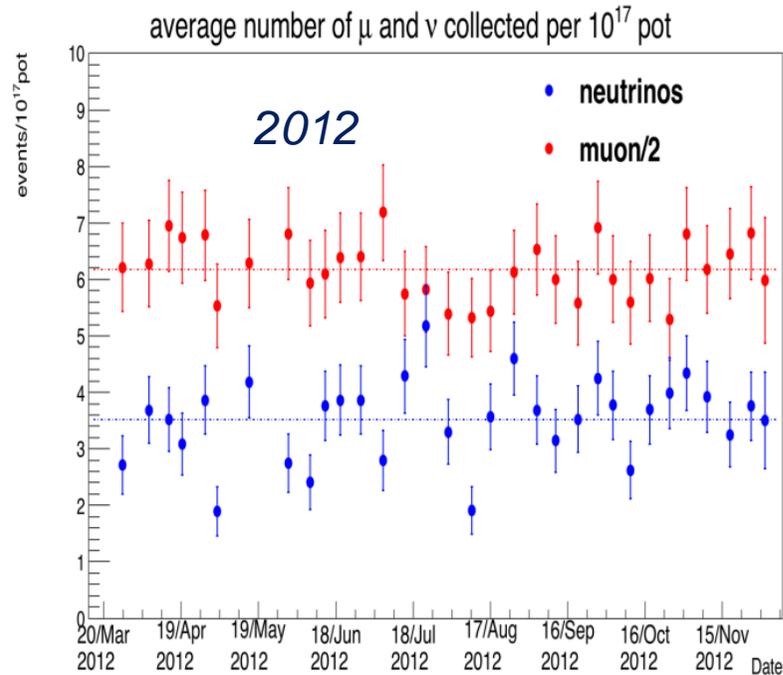
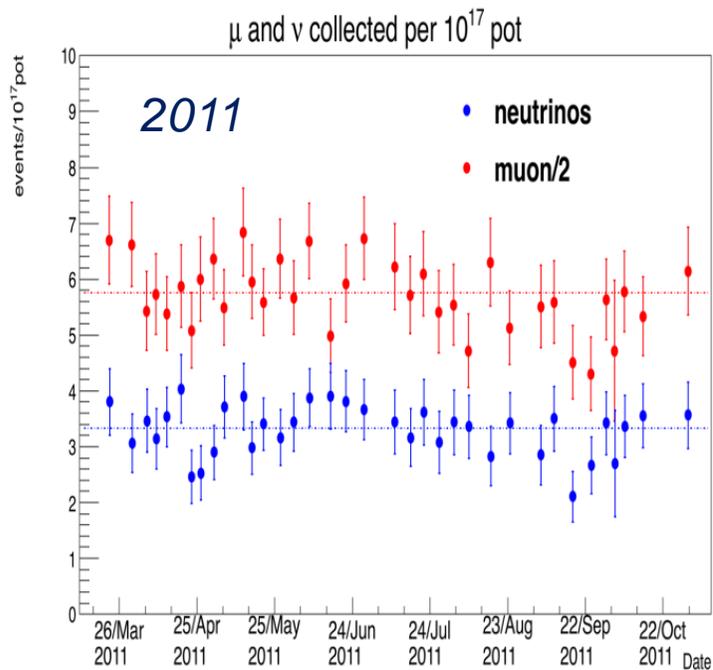


54000 electronic ch, low noise charge amplifiers + digitizers, S/N > 10



ICARUS: summary of collected data with CNGS

- A total sample of 2650 ν interactions corresponding to $7.93 \cdot 10^{19}$ over $8.6 \cdot 10^{19}$ pot collected has been filtered, scanned & preliminarily analyzed
- Distributions of collected neutrinos and of beam related μ s normalized by 10^{17} pot statistics and DAQ efficiency: 3.4 vs 12 μ s events on average



Data are consistent within 6% with MC predictions for corresponding exposure

Cosmic Ray Tagger

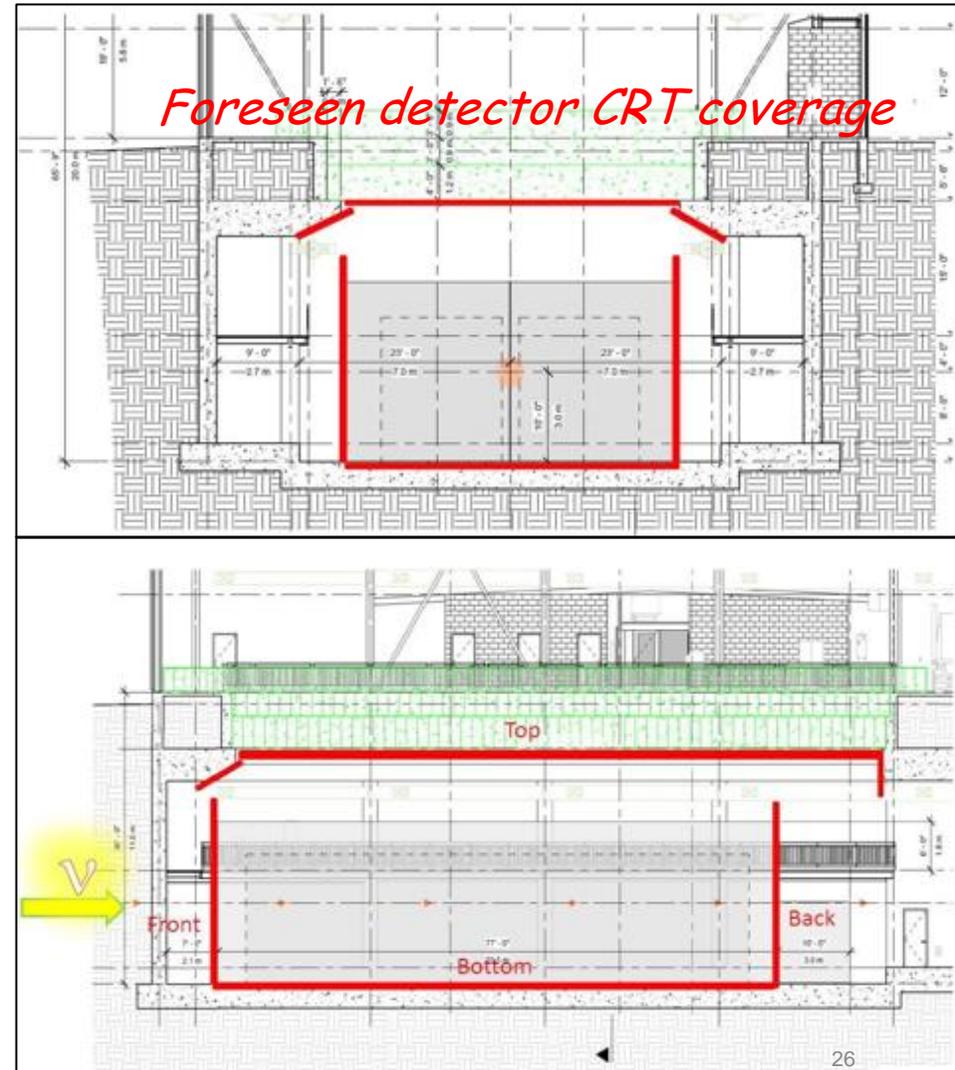
Design and development of the CRT is under way, as a common tool to be applied to the three SBN detectors (T600, SBND, MicroBooNE).

The present solution involves plastic scintillators, with embedded optical fibres read by SiPMs.



The amount of coverage results from the balance between the need to efficiently tag external CR muons and not veto internal ν CC events with outgoing muons.

Presently 95% coverage is foreseen; US groups and CERN are working on material testing and electronics development



PMT calibration system

A time resolution of ~ 1 ns is required for an efficient rejection of the background but **PMT are affected by transit-time drift**.

Equalization of each single channel may be obtained by analyzing crossing muons or by routinely delivering a fast laser pulse to each PMT.

A **calibration system**, made by fused fiber splitters, optical switches and optical patch-cords, has been designed and an optical fiber will be installed for each PMT.

The system will include a fast laser diode, a $1 \times N$ optical switch and 25 (1x16) or 50 (1x8) fused optical splitters, in addition to the necessary optical feed-throughs and patch-cords.

The internal part has been defined (50/125 optical fibers), but some **critical issues**, such as the availability of high-performance (vacuum tight) fiber feed throughs are **under study**.

An upgraded electronics

- Architecture of ICARUS electronics is based on analogue low noise “warm” front-end amplifier, a multiplexed 10-bit 2.5 MHz AD converter and a digital VME module for local storage, data compression & trigger.
- A signal to noise ratio > 10 and ~ 0.7 mm single point resolution were obtained at LNGS run, resulting in precise spatial event reconstruction and μ momentum by multiple scattering.
- *Some limitations:* asynchronous sampling of ch.s within 400 ns sampling-time slightly affecting MCS measurement, data throughput mainly due to VME.
- *Some relevant ongoing changes/improvements:*
 - Serial ADCs (10-12 bits, one per channel) in place of the multiplexed ones;
 - *Synchronous* sampling of all channels (400 ns sampling time) of whole detector;
 - Digital part contained in a single, high performance FPGA per board, that handles signal filtering, organizes information provided by the serial ADCs;
 - Housing/ integration of electronics onto detector; serial bus with optical links for faster transmission.



*From 595
to 10 liters*

